XXII. "Tables of Temperatures of the Sea at various Depths below the Surface, taken between 1749 and 1868; collated and reduced, with Notes and Sections." By Joseph Prestwich, F.R.S., F.G.S. Received June 4, 1874.

(Abstract.)

This paper was commenced by the author more than twenty years since, with a view to the geological bearing of the subject, but was for some years unavoidably interrupted. It has now been brought down to 1868, the date of the 'Lightning' expedition, when the subject was taken up by Dr. Carpenter, by whom it has since been so ardently and ably carried on. Nevertheless, as Dr. Carpenter's work relates almost solely to recent investigations, the author considers that there is yet considerable interest attached to the work of the earlier observers from 1750 to 1868, though he feels that much of it is necessarily superseded by the great and more exact work subsequent to 1868. He is aware that the older observations have also not been deemed reliable on account of the error caused by pressure on the thermometers at depths; but this is far from applying to the whole of them, as that error was taken into account so early as 1836, if not before, and a large number of these observations are equally reliable with the more recent ones, while the greater part of the others admit of corrections which render them sufficiently available.

In 1830, Gehler gave a list of 226 observations, and D'Urville, in 1833, tabulated 421 experiments according to depths. The present paper contains a record of about 1300 observations, which are arranged according to the degrees of latitude:—1st, for the northern hemisphere; 2nd, the southern hemisphere; 3rd, inland seas. They are all reduced to common scales of thermometer, measure of depth, and meridian. Their position is given on a map of the world, and the bathymetrical isotherms from the Poles to the Equator, based on the correct and corrected observations, are given in a series of ten sections. The author does not claim for these observations the exact value, or the unity and completeness of plan, of the more recent ones, while, as compared with them, the depths at which they were made are on the whole very limited; still they include a few at great depths; and as they extend over much ground that has not been covered by the expeditions of the 'Lightning,' 'Porcupine,' and 'Challenger,' he trusts that these Tables may be of some use as complemental to these later researches, and as bringing together and reducing to a common standard, observations scattered through a large number of works and memoirs. At the same time, the author would observe that he thinks it due to our many distinguished foreign colleagues who have been engaged in the inquiry, and whose work seems but little known, that the results of their researches should be understood in this country. Their conclusions, which are in close agreement with those formed, entirely in-

dependently, upon recent and better data by Dr. Carpenter, acquire, from this concordance, additional force and value. The author was not at all aware himself, in the earlier part of the inquiry, how much had been done, and often found himself framing hypotheses which, on further examination, he found had been long before anticipated by others.

The first part of the paper consists of an "Historical Narrative," which embraces an account of the character, number, and position of the observations made by Ellis (1749), Cook and Forster (1772), Phipps (1773), Saussure (1780), Péron (1800), Krusenstern (1803), Scoresby (1810 and 1822), Kotzebue (1815), Wauchope (1816 and 1836), John Ross and Sabine (1817 and 1822), Abel (1818), Franklin and Buchan (1818), Parry (1819, 1821, 1827), Sabine (1822), Kotzebue and Lenz (1823), Beechey (1825), D'Urville (1826), FitzRoy (1826), Blossville (1827), Graah (1828), Bérard (1830), Vaillant (1836), Du Petit Thouars (1836), Martins and Bravais (1838), Wilkes (1839), James Ross (1839), Belcher (1843 and 1848), Aimé (1844), Kellett (1845), Spratt (1845–1861), Dayman (1846), Armstrong (1850), Maury, Rogers, Bache (1854–57), Pullen (1857), Wüllerstorf (1857), Kündson (1859), E. Lenz (1861), Shortland (1868), Chimmo (1868).

The second part relates to the "Method and Value of the Observations." Wanting a reliable self-registering thermometer, the early observers, for a considerable time, used a machine contrived by Dr. Hales to bring up water, by means of a bucket with valves, from the depth at which the temperature was to be taken. This was used by Ellis, Cook, Scoresby, Wauchope, and Franklin, and one of a form improved by Parrot was employed by Lenz. Scoresby's observations in the seas around Spitzbergen are of much interest. He showed that while at the surface the temperature varied from about 29° to 42°, the temperature at depths of from 2000 to 4000 feet was generally about 34° to 36°; and there is reason to believe that, with the very slight corrections suggested by Lenz's subsequent researches, most of them are correct within a fraction of a degree.

The most remarkable readings, however, taken with this apparatus were those obtained by Lenz in Kotzebue's expedition of 1823. He applied to the observations a correction founded on Biot's law of the variations of temperature experienced by bodies in passing through mediums of different temperature, and determined the lowest temperatures hitherto noted in intertropical seas. Thus, one sounding in mid-Atlantic, 7° 21′ N. lat., at a depth of 3435 feet, gave a corrected reading of 35°·8 F., and another at a depth of 5835 feet, in mid-Pacific, 21° 14′ N. lat., gave 36°·4 F., the surface temperatures being 78°·5 and 79°·5. His observations on the specific gravity of sea-water are also valuable.

Saussure and Péron used thermometers surrounded with non-conducting substances, so that they might pass through the warmer upper strata of water with little change. Saussure's experiments deserve notice, inasmuch as, after applying a correction, they recorded, at that early period, for

the Mediterranean, at a depth of 1000 to 2000 feet, a temperature, so nearly right, of 55°·5.

Sir John Ross and Admiral Spratt sometimes used Six's thermometers, and at others took the temperature of the silt brought up from the bottom. The former obtained readings of 28°·5 F. for Baffin's Bay, and the latter of about 55° for the Grecian archipelago, agreeing therefore closely with good thermometrical observations.

Phipps used a differential overflow thermometer invented by Cavendish, but it was not found to answer. This form of instrument remained in abeyance until a greatly improved form of it was contrived by Walferdin (*thermomètre à déversement*) in 1836. It was used by Martins and Bravais in the Arctic seas, and by Aimé in the Mediterranean, and was said to give very satisfactory results. Aimé also used another somewhat similar instrument, which, at a given depth, was reversed and then hauled up. These instruments have the great advantage of being free from errors arising from the shifting or immobility of the index. It is not clear why their use was abandoned, except that they were difficult to construct and not generally known.

Six described his thermometer in 1782; but the first person to use it was Krusenstern, in 1803. It did not come into general use for deep-sea observations until the Arctic voyages of Ross and Parry, after which date it was, with the exception of Lenz's and Aimé's, employed for that purpose on all the expeditions sent out by foreign governments, as well as by our own. The necessity of protecting the instrument against pressure was early insisted upon by Lenz, Arago, Biot, and others; and there is reason to believe that protected thermometers were used by D'Urville and Bérard, for their observations in the same Mediterranean area show a remarkably close agreement with those recently made by Dr. Carpenter, with protected instruments, at and below depths of about 200 fathoms, the results being:—

D'Urville (May 1826).	Bérard (Nov. 1830).	Carpenter (Aug. 1870).
Surface ....64°·1 F.	Surface ....67°·1 F.	Surface....73°·5 F.
1062 ft.....54°·2	3189 ft.....55°·4	2958 ft.....55°·5
3189 ft.....54°·7	6377 ft.....55°·4	7968 ft.....54°·7

It was, however, on Du Petit Thouars's voyage of 1836 that the first special steps were taken to protect the thermometer against pressure. For that purpose an improved instrument of Bunten's was provided, and this was enclosed in a strong brass cylinder. Fifty-nine observations were made, of which Arago reported that 21 might be considered perfectly good. Temperatures of 36°, 37°, and 38° F. were recorded at depths (900 to 1100 *brasses*) in both the mid-Atlantic and mid-Pacific; while in one case, in taking a sounding at a depth of 12,271 feet near the equator in the Pacific, the instrument came up crushed, but with the index fixed at 34°·8 F. (1°·6 or 1°·7 C.). In a certain number of cases (24) the

pressure forced water into the cylinder. For these corrections were made.

In 1839, MM. Martins and Bravais made a series of observations in the sea between Norway and Spitzbergen with instruments carefully protected against pressure by means of glass tubes or metal cylinders. They used both self-registering thermometers (*thermomètrographes*) and Walferdin's self-registering overflow thermometers, sending down two to four of each in every sounding, and taking the mean of the readings. These probably are amongst the most accurate observations on record. To a great extent they confirm those of Scoresby; and they further showed that the bottom-temperature near the Spitzbergen glaciers was about 29° F. None of the soundings exceeded 3000 feet.

In 1857, the late Admiral FitzRoy furnished Captain Pullen with thermometers specially constructed to resist pressure, and some very interesting, though somewhat variable results, were obtained therewith. On two occasions a temperature of 35° F. was recorded—one in the Atlantic, 26° 46′ S., at a depth of 16,200 feet, and the other in the Indian Ocean, at a depth of 13,980 feet.

With regard to the many observations made with unprotected instruments, they mostly admit of correction, which renders them available. Such corrections have been independently computed, with little difference, by Du Petit Thouars, Martins, Aimé, and the late Dr. Miller. The author, taking the mean of their estimates, uses as a coefficient −1° F. for every 1700 feet of depth.

In the third part of the paper the author shows the "State of the Question at the date of the Lightning Expedition." Ellis, Forster, Péron, and others early remarked on the decrease of temperature at depths in temperate and tropical seas, but it was not until 1823 that Lenz showed that a temperature of 35° to 36° existed at greater depths in those seas. Notwithstanding this, D'Urville in 1826, misled by incorrect readings obtained by previous observers with uncorrected instruments, and in the absence of sufficiently deep observations of his own, was led to believe that the temperature in open seas at and below a depth of 3214 feet (600 *brasses*) was nearly uniform at 39°·8 F. (4°·4 C.), and that between the latitudes of 40° and 60° there is a belt of a like nearly uniform temperature. A few years later, Arago, discussing the results obtained by Du Petit Thouars, insisted that they effectually disproved this hypothesis. Nevertheless, in 1839, Sir James Ross made the same mistake as D'Urville, and unfortunately obtained for it a wider circulation, which seems, however, to have been almost altogether restricted to this country. Still, Ross's numerous observations, when viewed under correction, are of considerable value, though the author considers that some error has occasionally crept into that uniform reading, so often recorded, of exactly 39°·5. Both D'Urville and Ross wrote under the opinion that sea-water, like fresh water, attained its maximum density at a tempera-

ture of between 39° and 40°,—a point that had been investigated and disproved by Marcet in 1819, approximately determined by Ermann in 1822, and which was finally settled by Despretz, in 1837, at 25°·4 F.

While the law of the decrease of temperature with the depth, in both the great oceans, to a point but little above the zero of Centigrade was being established, experiments had been carried on in polar seas showing, on the contrary, that the temperature at depths was higher than the average surface-temperature. The careful experiments of Scoresby and of Martins fully established this for the Arctic seas, and those of Ross, after correction, establish the same fact for the Antarctic Ocean. In one part, however, of the Arctic seas this rule has not been found to hold good; for, in Baffin's Bay, the experiments of John Ross, Sabine, and Parry, at depths of from 600 to 6000 feet, agree in showing a decrease of temperature of from 30° to 32° near the surface, to 29° and 28°·5 at the greatest depths attained. There are also two instances given of yet lower temperatures.

Nor were observations wanting in inland seas. Those of Saussure, D'Urville, and Bérard had indicated generally that, in the Mediterranean, the temperature decreased to a depth of about 1200 feet, after which it remained uniform at from 54° to 55° F.; and, in 1844, Aimé instituted a series of experiments which resulted in showing that the diurnal influence ceased to be sensible at a depth of from 16 to 18 metres, and the annual variation at a depth of from 300 to 400 metres, below which the temperature remained constant at 12°·6 C. (54°·6); and this he showed to be the mean winter temperature of the area of the Mediterranean, over which his observations extended. These observations were confirmed, for the Eastern Mediterranean, by those of Admiral Spratt. His first experiments in the Grecian archipelago showed, at a depth of 1200 feet, a temperature of 54°·5 to 55° F., while the later ones, at greater depths in the open sea, give, after correction, a temperature of about 55°. In the Red Sea, Captain Pullen found that while the surface-temperature varied from 77° to 86° F., it fell to 70° or 71° F. at 1200 to 1400 feet, below which it remained uniformly the same to the greatest depth he attained of 4068 feet. Some curious results were obtained in 1803–6 by Dr. Horner in the Sea of Okhotsh. The surface-temperature was 46°·4 F.; and the author finds (after correcting the original readings) at 360 feet a temperature of 28°, and at 690 feet of 28°·6, which is almost exactly that determined by Despretz as the temperature of sea-water at the moment of congelation.

The cause of the decrease of temperature with the depth in the great oceans was early investigated by physicists. Humboldt concluded that "the existence of these cold layers in low latitudes proves the existence of an undercurrent flowing from the poles to the equator." D'Aubuisson and Pouillet took the same view. D'Urville went further, and remarked that "it is rather a transport nearly in mass, and very slow, of the deep waters of high latitudes towards the equator," and that from his zone of

40° to 60° lat. there are two insensible currents—a lower one towards the equator, and an upper one towards the poles. Arago saw no other explanation than "the existence of submarine currents carrying to the equator the bottom waters of the icy seas."

We are, however, indebted to Lenz for a full and philosophical review of the whole subject in 1847. After showing that all the facts proved the existence of a temperature of from 34° to 35° F. at depths in the tropical seas, and that this could only be maintained by a constant slow undercurrent from the poles to the equator (which, on the other hand, must necessitate the transfer by an upper current of the equatorial waters to the poles), he proceeds to show by a series of observations, chiefly those of Kotzebue, and by a diagram, that a belt of cooler water existed at the equator, and that the temperature, at equal depths, was lower there than a few degrees to the north and south of it; and he concluded that this arose from the circumstance that the deep-seated polar waters there met and rose to the surface. As corroborating this view, he showed that the waters in the same zone were of lower specific gravity, a fact that had been before noticed by Humboldt.

The author then proceeds to consider some "General Conclusions." Some of these have now been better established by the more recent expeditions and by the researches of Dr. Carpenter. Taking, however, other areas, he shows that in the Arctic Ocean the bathymetrical isotherm of 35° is deepest on the west of Spitzbergen, while nearer Greenland and again nearer Norway the deep waters are colder. The several isothermal planes of 40°, 50°, 60°, 70°, and 80° are then traced southward, attaining their maximum depth between 50° and 40° lat., and rising thence towards the equator. Section No. 2, from Baffin's Bay to the equator, shows that the higher isotherms are not prolonged so far north as on the first line, and that the water at the bottom of the bay is colder than in the Spitzbergen seas, approaching much nearer that of its maximum density and of its point of congelation; whence he concludes that this is the main source of supply of the deep-seated cold waters in the Atlantic, which, after attaining their greatest depths between latitudes 40° to 50° N., are found 3000 to 4000 feet nearer the surface on approaching the equator.

In the South Atlantic, the bathymetrical isotherms show lesser curves; and while the isotherm of 40° crops out between the lat. of 50° and 55°, that of 35° is prolonged into high southern latitudes on a nearly uniform plane of 7000 to 8000 feet deep.

In the Pacific, the sections show that, notwithstanding there is no appreciable polar current through Behring's Straits, the bathymetrical isotherms of 60°, 50°, and 45° do not extend so far north as in the Atlantic, while that of 35° is apparently not prolonged beyond 60° N. lat. As the presence of temperatures lower than those which prevail in

parallel latitudes in the Atlantic cannot be due to north polar waters, and seems more than could be maintained by local influences, the author concludes that the effect may probably be due to waters from the Antarctic Ocean, of the presence of which the low temperatures at depths throughout the Pacific affords evidence, passing, in the absence of any counter flow, to the extremity of the North Pacific, where they are thrown upwards by the rising slopes of the ocean-bed, as on banks in open oceans. On the other hand, in the South Pacific the conditions seem very similar to those in the South Atlantic. The bathymetrical isotherms appear, however, to be prolonged further south than in the South Atlantic, which arises possibly from the circumstance that as none, or comparatively none, of the warm equatorial water can pass into the Arctic Ocean, a larger proportion passes into the Antarctic seas.

In the Southern and Indian Oceans the conditions seem analogous to those of the North Pacific, only they are more masked by the high surface-temperatures of the Arabian Gulf.

The author agrees in the opinion which has been advanced of the flow over the ocean-bottom of cold undercurrents at and below 35°, one from the north and the other from the south pole to the equator, and of their rise in the equatorial regions of the Atlantic. They must, then, necessarily tend to disperse and escape into other areas; but whether by a movement in mass of the upper strata, or by currents in more definite channels, or by both causes combined, remains to be proved by further research. He inclines to the latter view. He would suggest the question whether the Gulf-stream, together with others which seem to originate or acquire additional power in equatorial seas, such as the Guinea and Brazilian currents, may not receive either their initial start or be strengthened and maintained by the surging-up of the Arctic and Antarctic waters at the equator, while another portion of those waters may be deflected back in insensible currents to polar regions. In the same way some of the great currents of the North Pacific may arise.

The paper concludes by a review of the other causes connected with these conditions, by a consideration of the normal isotherms of the polar regions, and by a comparison of the temperatures of inland seas, which are dependent on local climatal conditions, with those of the great oceans, which are subject to such vast distant influences; and he directs attention to the important bearing which these questions of oceanic physics have on many geological problems.